Heat energy from a shallow geothermal system in Glasgow, UK: performance evaluation design

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Short communication

Heat energy output from a shallow geothermal open loop system in Glasgow: Performance evaluation Design, installation and performance.

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Abstract

This study reports on the actual energy and economic performance of a water source heat pump recently installed and operated at a Glasgow Subway Station using subsurface water ingress to provide heating and domestic hot water. This follows from a previous publication (Hytiris et al., 2016) that detailed the empirical measurements and design of a heating system designed on the basis of a fifteen-month monitoring period of the water flow and temperature. The perennial water flow at a relatively high temperature enabled the system to operate more efficiently than a typical heat pump system with boreholes or trenches. The performance of the water source heat pump has been monitored for a four-month period and the coefficient of performance as well as energy saving is reported in the present study.
The findings of this study indicate the energy, carbon and financial benefits of the heating system, but also highlight key issues during the operation in such a demanding underground environment. Further renewable heat potentials for the rest of the subway network and opportunities to commercialize the excess heat energy output are explored.

Keywords:

Renewable heat, energy, geomorphology, town and city planning.

List of notation:

WSHP	Water Source Heat Pump
COP_H	Coefficient of Performance
DHW	Domestic Hot Water
BS	British Standard
EN	European Norm

1. Introduction

The quest for replacing fossil fuel for energy is becoming stronger year on year. In the EU as well as in the UK, governments are implementing more renewable energy projects with a view to significantly reducing/decarbonising the energy sector by 2050, in line with legislative mandates (such as the *UK Climate Change Act, 2008*). However, progress in decarbonising heating continues to be slow (Chaudry et al., 2015). The use of shallow geothermal heat is one such potential source that can greatly reduce CO_2 emissions (Vangkilde-Pedersen, 2012). In Europe as well as around the world, a lot of research is underway seeking methods to exchange heat with the ground and provide thermal energy for heating and cooling of buildings. Tunnels involve a large volume of ground and surface for heat exchange and some examples of energy tunnels have been recently proposed to be investigated (Di Donna and Barla, 2016).

A shallow geothermal heat source is available in the centre-west of Glasgow city, where a circular underground passenger railway system built in 1896 (Civil Engineering, 1996) has continually been in operation since. The system comprises of twin tunnels connecting fifteen stations along a route length of just over ten kilometres (Figure 1). Due to the age and methods of construction used in earlier times, a large volume of water from ground sources and surface watercourses enter the tunnel system. Such water ingress enters via weaknesses within the tunnel lining or trackbed or installed drainage pipes or channels throughout the entire tunnel system. This is currently problematic due to both its quantity and quality that could potentially interfere with the subway operation and needs to be constantly managed.

Once water enters the tunnel network, the flows are eventually directed to the pumping station sumps either via a drainage channel set within the concrete trackbed between the running rails or via drainage pipes, dependant on the location of sumps and discharged through a pumping system. In a previous publication (Hytiris et al., 2016) we detailed water flow and water temperature measurements carried out over a 15-month period at 21 different points within the network of the underground tunnels and platforms. The points of highest water influx were identified, and the heat energy content of each was calculated. Working from these data, several options were identified for capturing the water and diverting it to a WSHP to recover heat. A final design for a pilot system within the tunnels was developed. The actual utilisation of this vast untapped resource to generate heat for one of the Subway stations was the main objective of the present study. Identifying the quantity and quality of this waste water in the Subway was critical, in order to examine the likelihood of harvesting heat energy with the use of a Water Source Heat Pump (WSHP). The aim was to ascertain the potential of using the Subway's water ingress in a Station with perennial flow. This would demonstrate the viability of such a heating system, reducing the installation cost due to the absence of boreholes or trenches which are typically associated with a conventional WSHP.

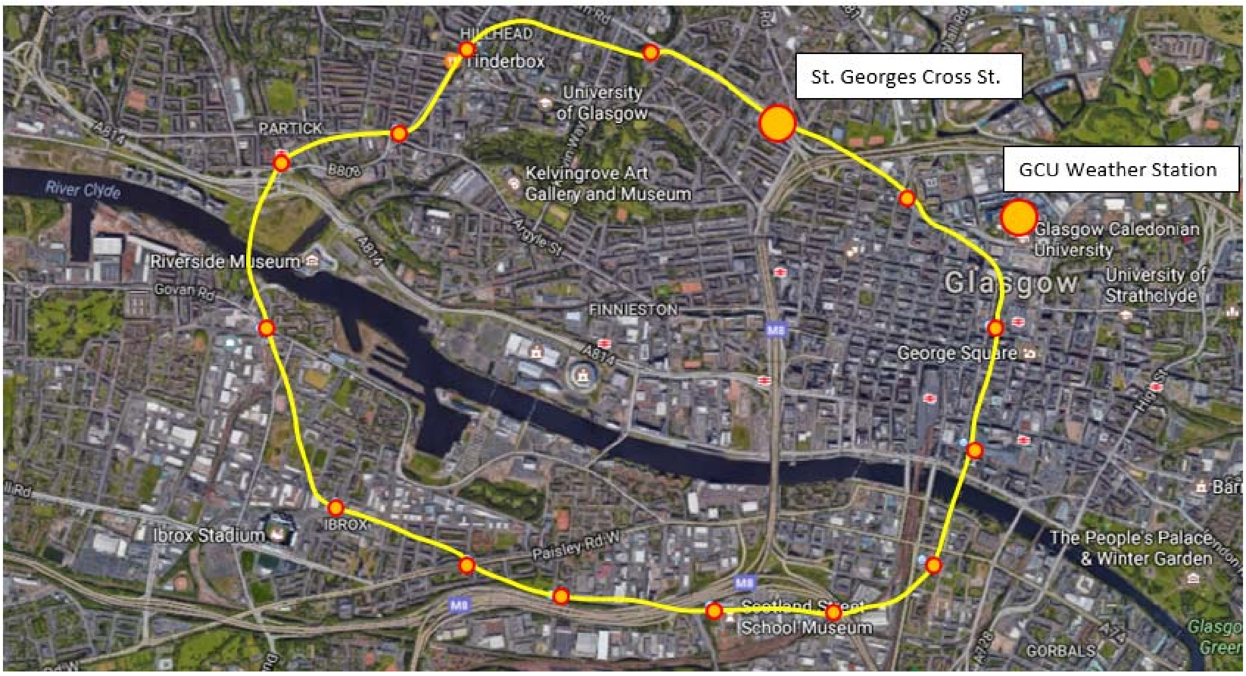

Figure 1: The Glasgow Subway map
Source: Based on Google Earth

The water ingress into the subway tunnels requires constant emptying of water collected in sumps. The sumps (Figure 2) are generally flat bottomed rectangular chambers formed within the tunnel invert. The pumping stations inside each sump are equipped with submersible pumps which pump out and discharge the water into the sewerage network adjacent to each station.

Figure 2:Sump located between the rail tracks in the Glasgow Subway system

2. Methods and Materials

It should be emphasised that half of the subway tunnelling was made of 'cut and cover' and consists of man-made-ground of unknown physical and mechanical characteristics such as compaction, nature, density, permeability etc. All stations are made by 'cut and cover' techniques incorporating large caisson (Casely and Hamilton, 1976)

It was therefore not possible to theoretically determine the likely heating energy that could be produced from the water ingress, since the thermal conductivity of the soil is unknown. Any estimation of the soil conductivity based on standard values would be meaningless since there is no 'standard' soil present around the tunnel system. As such, only an empirical derivation of temperatures and water flow would be the sensible approach to design the water source heat pump.

2.1 Water source heat pump installation

We selected the location of field trial on the basis of four factors: shortest distance from the "source" (sump –at the track level) to the "sink" (station's office – at concourse level); constancy of water flux; water quality, especially iron content and constant water temperature. On this basis St. George's Cross Station was selected for the feasibility study (see location on Fig 1). The water flow rate at this station are shown in Table 1 (mean water flow = **2.75 l/s**) and the water temperature variations are in Figure 3 (mean temperature = **14.2^{o}C**). Chemical analysis of water quality indicated very low levels of iron (Fe = **0.042 mg/l**)) throughout the monitoring period.

Based on these data, a trial heat pump installation was designed and delivered at site in late 2015 and commenced operation in the last quarter of 2015.

Table 1: Water Flow in sump 1 at St George's Cross Station

WF1: Water flow (sump 1)		
Month	Year	WF1 (l/s)
May	2014	6.7
June	2014	6.3
July	2014	5.3
August	2014	3.9
September	2014	1.9
October	2014	1.8
November	2014	1.8
December	2014	2.0
January	2015	2.1
February	2015	2.2
March	2015	1.5
April	2015	1.6
May	2015	1.5
June	2015	1.4
July	2015	1.3
	Average Flow	**2.75**

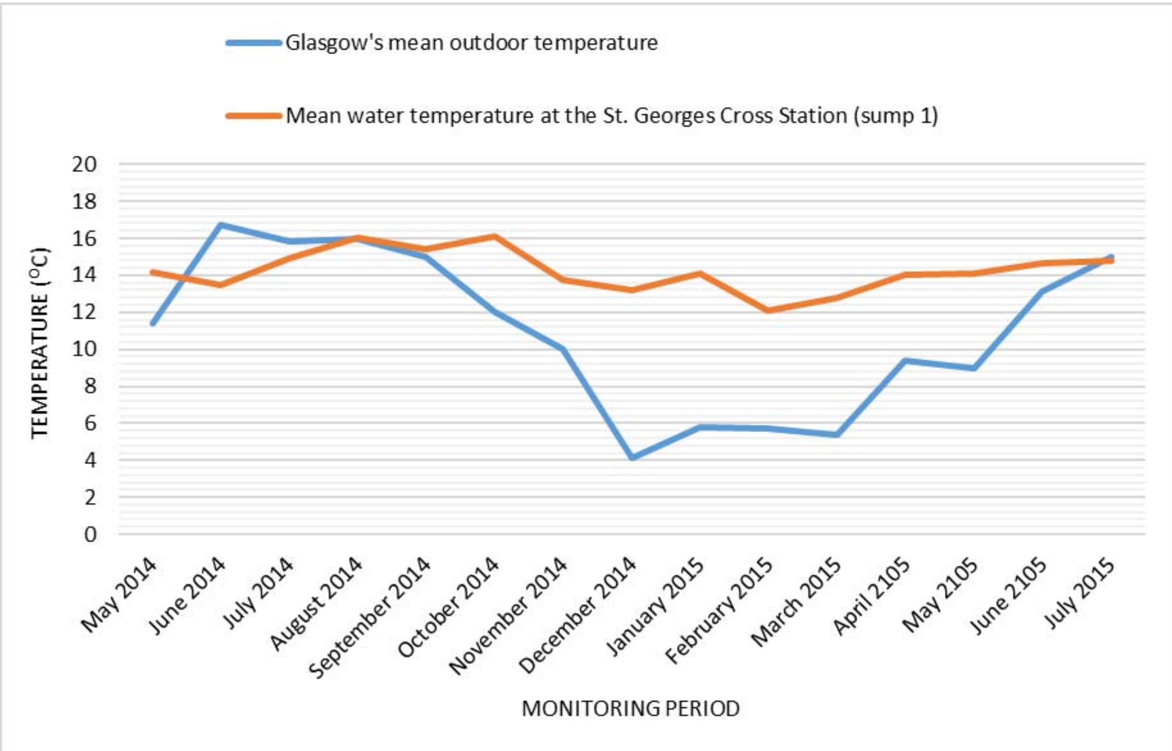

Figure 3: Sump's 1 water temperature

Table 2: Glasgow's monthly rainfall

MRF: Monthly rainfall					
Month	Year	MRF (mm)	Month	Year	MRF (mm)
November	2013	45,80	October	2014	69,20
December	2013	113,00	November	2014	39,60
January	2014	78.80	December	2014	72.60
February	2014	75.80	January	2015	95.00
March	2014	56.40	February	2015	36.20
April	2014	48.80	March	2015	60.00
May	2014	39.00	April	2015	27.40
June	2014	34.43	May	2015	77.60
July	2014	18.60	June	2015	29.20
August	2014	40.80	July	2015	110.07
September	2014	4.00			

While Fig 3 indicates the water temperature had been relatively constant, substantial variation in water flow could be seen in Table 1. Among other factors, it is possible that the variations in water flow was due to changes in rainfall – rainfall and ground water level, which are invariably connected hydraulically to the surrounding aquifer systems is well known (Furrey and Gupta, 2005, Freeze and Banner, 1970, Ngongondo, 2006). This is partly confirmed by the rainfall readings in the vicinity (Figure 4) which shows water flow rates at the sump against monthly rainfall measured at a nearby reference weather station (Glasgow Caledonian University [GCU] weather station, see Fig 1 for location). It could be seen in Fig 4 that the water flow rate follows the monthly rainfall pattern with an approx. 5 to 6-month lag time. It is quite clear that late 2013 / early 2014 had a lot of rain and that has led to much higher water flow in May/Jun 2014, whereas the later part of that year (2014) was relatively dry, which is reflected in the reduced water flow in the following year (Figure 4). Nevertheless, the water flow never dropped below 1.5 l/s even when there was little or no rain.

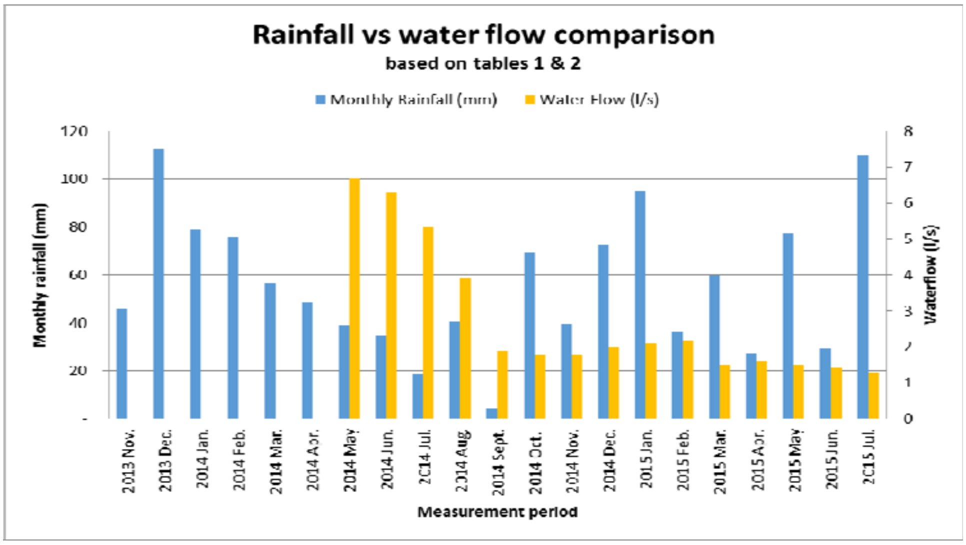

Figure 4: Rainfall vs water flow comparison

We have previously reported that the total heat load at St George's Cross Station was 5.2 kW (Hytiris et al., 2016). Thus, a 9kW WSHP was required to meet this station's heating and domestic hot water demand. Figure 5 shows the installed heat pump system while the new low temperature fan coil radiators with local controls and set point adjustments are shown in Figure 6.

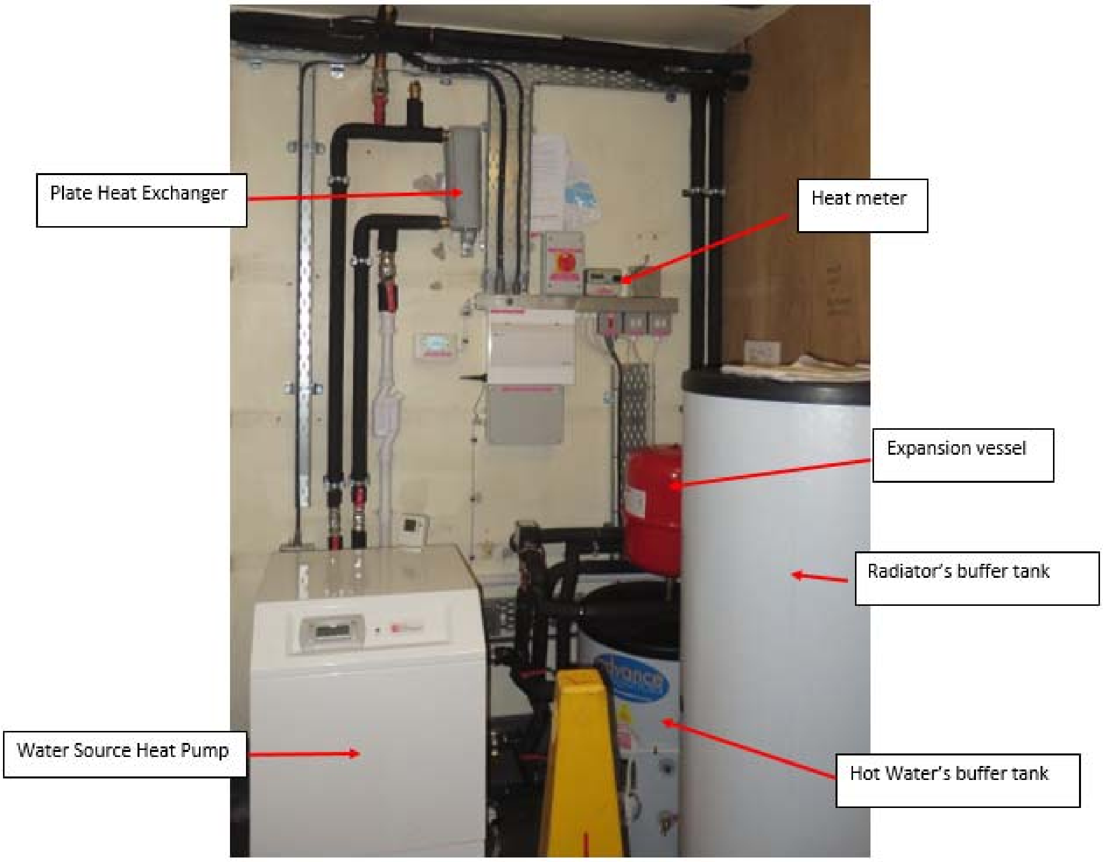

Figure 5: The plant room with the WSHP (left) and the buffer tanks (right)

Insulated copper pipes (∅ 28mm to ∅ 15mm) run from the track level to the concourse level without interfering with the Subway's kinematic envelope. All equipment is constructed of non-combustible materials and cables are low smoke and fume, to comply with fire regulations (Fire Precautions, 2009). A water pump (Lowara SC 205T 01) was positioned within the sump to pump the water to the heat pump at a distance of 25m (Figure 7). The extraction rate, according to the design was set to 30 l/min (0.5 l/s) since this was adequate to provide both space heating and domestic hot water at this station. Additionally, the hot water buffer tank has a 4kW immersion heater (back up for weekly pasteurisation cycle) and a strainer (water filter) installed prior to the heat exchanger to prevent any blockage due to silt or other substances that could potentially cause blockages to the system (Figures 8 & 9).

Figure 6: One of the four new radiators at the Station’s corridor

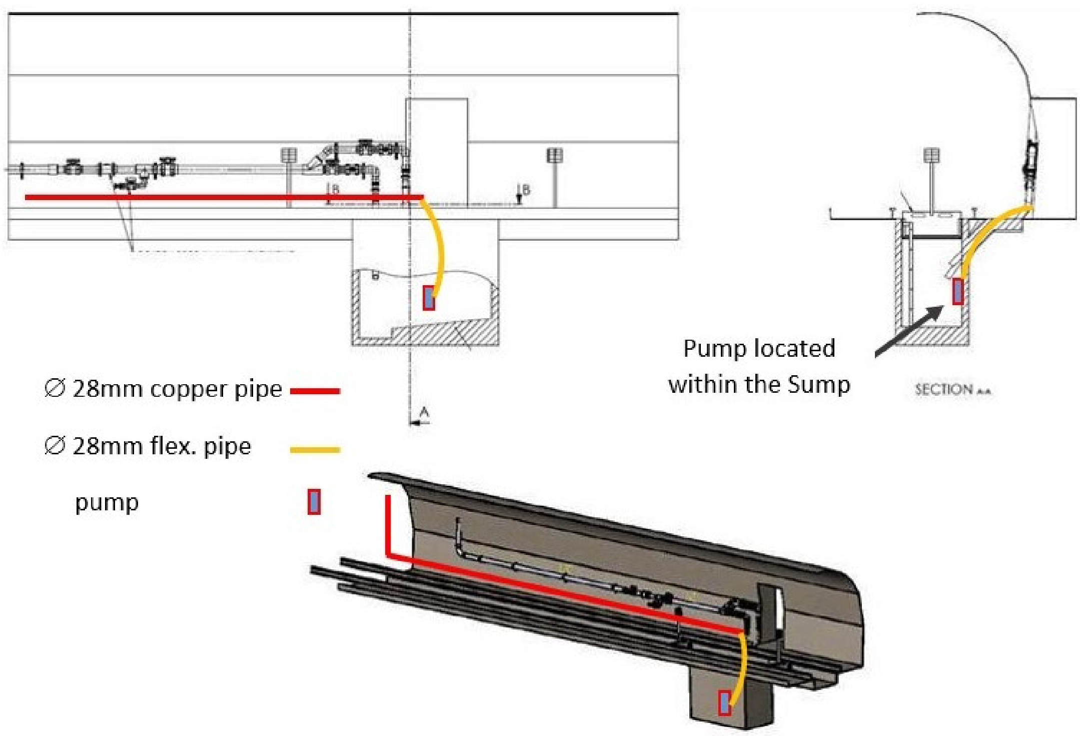

Figure 7: The pump positioned within the sump (track level)

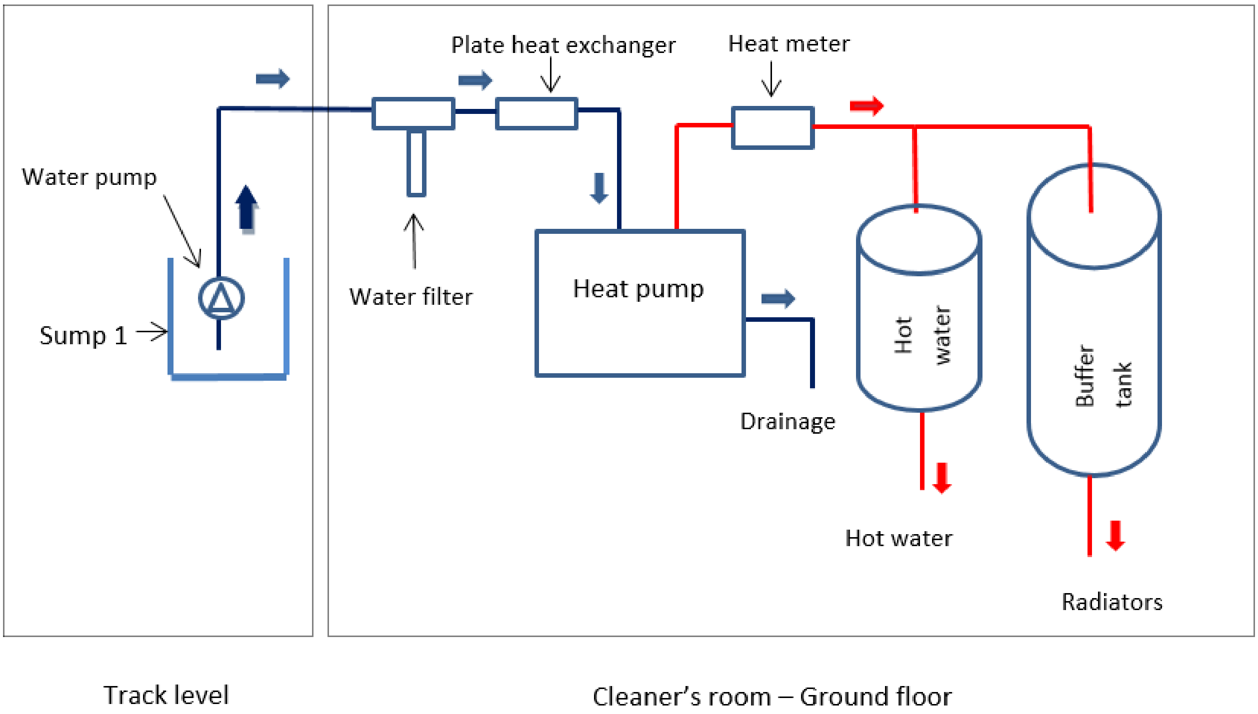

Figure 8: St. Georges Cross heating system's diagram

Figure 9: The water filter at the plant room

3. Results

3.1 Coefficient of performance

The case study location (St George's Cross Station) has been operating 18 hrs per day for seven days a week during the trial period. A buffer tank feed the station's hot water at 50 degrees Celsius. Once a week, the hot water system electrically raises the water temperature above 65 degrees Celsius to protect against Legionella disease. A room temperature of 21 degrees Celsius has been set and maintained during the operational hours at the station's premises.

In order to verify the above levels of performance a monitoring system has been installed (Figure 10) and readings obtained during the first 4 months of its operation. Figure 11 shows that there is an average heat energy output of 2.48 kW for each kW of energy input. The heat output includes both the hot water sent to the radiator coils as well as the water directed to the DHW buffer tank.

The current extraction of water for the WSHP system is 30 l/min to provide adequate heating and hot water to the station. This account for approximately a third of the water ingress into the sump, thus the operation of the water pump to pump out the water into the sewer system has been substantially reduced, providing further energy savings.

Figure 10: The heat input / output monitoring device

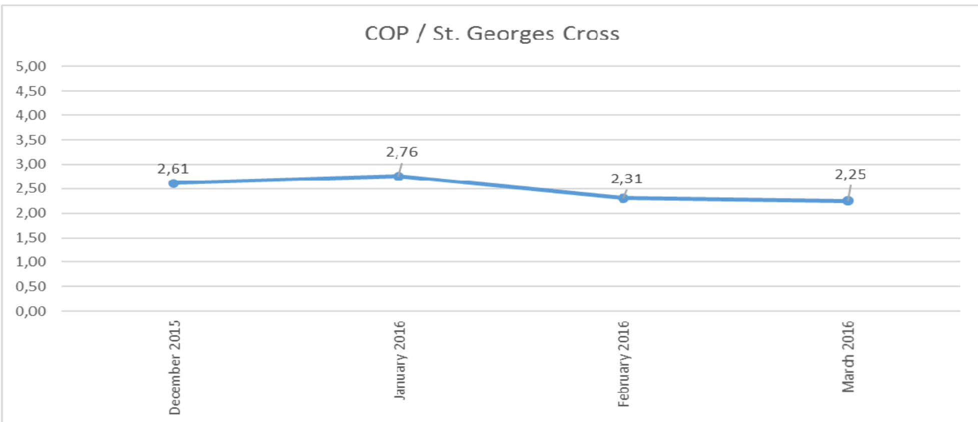

Figure 11: The WSHP's Coefficient of Performance (Average = 2.48) at the St. Georges Cross Station

3.2 Cost and carbon savings

The WSHP installed at St. George's Cross Station directly uses water from the adjacent sump without the need for digging boreholes or trenches. Due to this, the overall installation cost was kept low compared to a conventional WSHP system. According to the company that undertook this installation, in the absence of an average water flow in the sump of 2.7 l/s with a mean temperature of 14^{o}C, two boreholes of 25m depth each would have been necessary to provide the water for a typical 9kW WSHP installation. This would cost approximately £10,000 (Horizon Renewable Energy).

A third of the water ingress at this location is now being directed to the WSHP for the Station's heating and domestic hot water. The used water from the plant room is gravity-fed into the station's sewer. This has reduced the operation of the existing water pumps by a third, contributing to further cost savings both in terms of operation and maintenance of the pumps. The reason for extracting only a third of the sump's water was because that was all that was required to cover the Station's thermal needs. It would be possible to extract more heat from all of the water ingress provided a ready use for the heat could be found.

Prior to the installation of the WSHP system, the station was heated by electric fired heating system, which consumed 10 kW electricity for space heating only without including the energy input for the hot water. This has now been replaced with a 4 kW WSHP system with a 4 kW energy input (for a 9kW output of the WSHP). The new WSHP system provides not only space heating but also domestic hot water. Thus a 60% reduction in energy consumption has been achieved, leading to substantial improvement in the station's carbon footprint.

4. Lessons and conclusions

Several valuable lessons were learned during the trial period. The first was the importance of stakeholder involvement and education. Staff familiarity and expectations of the new heating systems was an issue that posed operational difficulties at the beginning. During the first month of operation the staff began to compare the slow but steady heat provided by the WSHP against the quick-fire electric system they were used to, before the trial. They complained about the working environment being 'too cold', however, these concerns were resolved through training and information sharing on the heating principles of the new systems (i.e. low grade but constant heat of the WSHP unlike an electric radiator, requires time to establish a steady ambient temperature).

Additional complications arose due to the challenging nature of the operational environment of a subway system. This was further exacerbated by the tunnel upgrade and cleaning works undertaken at that time (Spring 2016). After four months of the heating system's operation the system performance significantly dropped in March 2016. Diagnostics revealed that the heat exchanger was blocked with silt (Figure 5), believed to have been caused by the tunnel upgrading work. The water pump within the sump (Figure 8) was pumping the water to the WSHP but the heat exchanger could not cope due to a blockage at the heat exchanger. A new heat exchanger together with a strainer (water filter) was therefore positioned after the completion of all works in November 2016. With this new equipment in place, a period of new monitoring has been initiated and results expected in late 2017.

Any future works or any disruption of the current status with regards the water and the associated equipment within the sump could potentially result in a disturbance or a malfunction of the heating system. Even repositioning the water pump inside the sump that feeds the WSHP may cause a failure. The height between the bottom of the sump and the lower level of the pump is such that no silt can enter the heating system based on the current water quality. However, future repair works close to or within the sump may allow debris to enter the pump. If during future works the pump for some reason will be moved lower to the bottom of the sump, this may jeopardise the operation of the heating system. In order to protect the water pump and the associated equipment, a visual inspection of the water level and quality within the sump should be carried out prior to operating the WSHP to identify potential risks to the heating system.

A second water filter is proposed to be installed prior to the heat exchanger, parallel to the existing one. This would assist in a continuous operation of the heat pump. When one of the two filters is under inspection, the water could be directed to the second one and vice versa. This two filter system setup is expected to avoid any future system blockage and would further require only a fortnight check which could be accommodated by a member of Staff.

The present empirical case study provides evidence that a WSHP system could be rolled out across the entire subway network. However, further steps are needed before this could be a reality. Given the high capital costs likely to be associated with the deployment of such a system across the network, feasibility studies on potential heat usage must be carried out to ensure the full economic benefit from the water ingress is made. This could be achieved through a district heating system using the renewable heat incentive (RHI) schemes currently in place in the UK (Ofgem, 2017). Further integration with the heat mapping exercise currently underway in the region (Scottish Govt, 2016) is also needed to make this a reality.

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